

XII. QUE 94201

Basalt, 12 grams

Weathering Be



Figure XII-1. Photograph illustrating broken interior surface of Martian meteorite QUE94201. (NASA # S96-00376)

Introduction

Five sides of QUE94201 are rounded and polished with a remnant fusion crust while one side appears freshly broken (figure XII-1). The interior is coarse-grained, crystalline and glassy (Score and Mason, 1995). “Mafic-rich areas” (probably shock-melted glass), as large as 5 x 4 mm, were noted during preliminary examination. In thin section, the sample is made up of subequal amounts of homogeneous maskelynite laths and variable interstitial pyroxene. Maskelynite laths are up to 3.6 mm long.

QUE94201 is a basalt apparently similar (McSween *et al.*, 1996) to the dark, mottled lithology (DML) of Zagami. The REE pattern is strongly depleted in light rare earths.

The Fe-Ti oxide compositions indicate that this basalt

formed under more reducing conditions than the other shergottites (McSween *et al.*, 1996).

Petrography

Harvey *et al.* (1996) describe QUE94201 as a “*coarse-grained basalt, consisting of subhedral Fe-rich pigeonite and maskelynite*”. Most of the pyroxene and maskelynite grains exceed 1 mm in length (up to 3 mm) and are somewhat elongated (figure XII-2). The mineral mode is approximately 44% clinopyroxene (pigeonite to augite 77:23), 46% maskelynite, 2% opaques, 4% whitlockite, 4% mesostasis (table I-1). QUE94201 contains relatively high proportions of maskelynite and whitlockite compared with other shergottites. No melt inclusions were noted in the pyroxene.

The pyroxenes in QUE94201 are complexly zoned

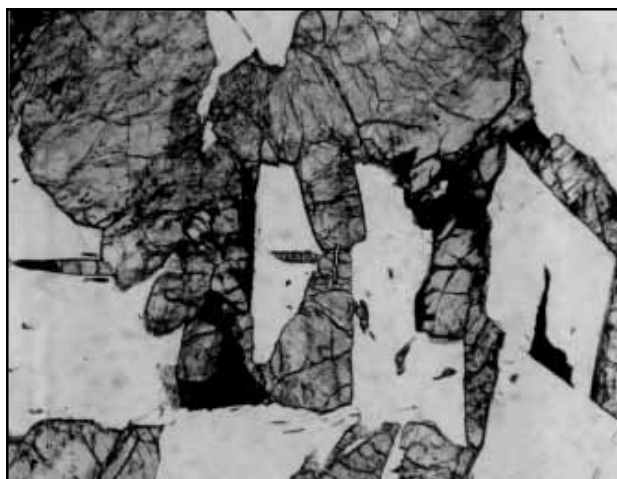


Figure XII-2. Photomicrograph of thin section of QUE94201,4 illustrating basaltic texture. Field of view is 2.2 mm.

(McKay *et al.*, 1996, Mikouchi *et al.*, 1996 and McSween and Eisenhour, 1996). The Mg-rich pigeonite cores are mantled by Mg-rich augite, which is, in turn, rimmed by Fe-rich pigeonite and strongly zoned to pyroxferroite. None of the cores appear to be cumulate phases, as was the case for Shergotty, Zagami and EETA79001B. Some of the pyroxenes in QUE94201 are sector zoned.

Interstitial to the pyroxene and shocked plagioclase, are a number of late-stage phases including large Fe-Ti oxides (ulvöspinel, rutile, ilmenite), whitlockite and large “pockets” of mesostasis similar to the “DN pockets” of Zagami (McCoy *et al.*, 1995). These “pockets” contain an intergrowth of silica and fayalite, as well as, maskelynite, whitlockite, Fe-Ti oxides, sulfides, minor augite, chlorapatite and a Zr-rich phase, probably baddelyite. Fayalite-silica intergrowths are also found in the cores of large skeletal phosphate grains adjacent to these pockets (Harvey *et al.*, 1996).

Shock features include maskelynite, mosaicism in pyroxene and large pockets of glass formed *in-situ*. The shock-melted glass is rich in phosphorous.

Mineral Chemistry

Pyroxene: Pyroxene zoning is extreme (figure XII-3), including sector zoning in the cores (Kring *et al.*, 1996, Mikouchi *et al.*, 1996, McKay *et al.*, 1996, McSween and Eisenhour, 1996). Harvey *et al.* (1996) report pigeonite zoning to Fs_{85} . Wadhwa and Crozaz (1996) and McSween *et al.* (1996) have determined

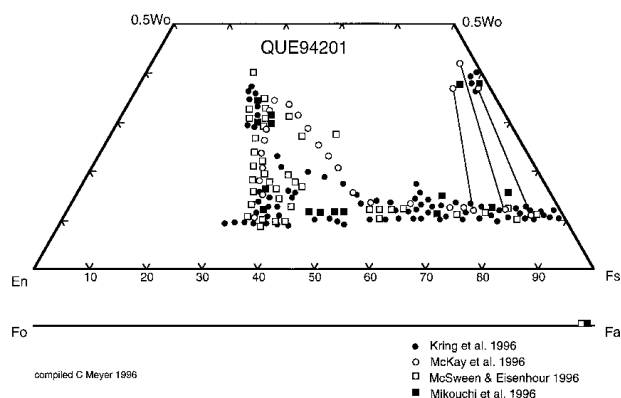


Figure XII-3. Composition diagram for pyroxene and olivine in QUE94201. Data are from Kring *et al.* (1996), McKay *et al.* (1996), McSween and Eisenhower (1996) and Mikouchi *et al.* (1996). Olivine is pure fayalite.

the REE patterns of the pyroxenes.

Plagioclase: Plagioclase (An_{66-52}) crystallized late in the crystallization sequence (McSween and Eisenhour, 1996). It has been shocked to maskelynite.

Whitlockite: QUE94201 contains more whitlockite than other SNC meteorites. The whitlockite has been studied by Wadhwa and Crozaz (1996) and is found to have a more extreme depletion of LREE than for any other shergottite.

Apatite: Mikouchi *et al.* (1996), McSween *et al.* (1996) and Leshin *et al.* (1996) also report minor chlorapatite.

Silica: Silica occurs as distinctive intergrowth with fayalite in “patches” up to 1 mm in-between pyroxene and plagioclase grains.

Olivine: Fayalite (Fa_{96-99}) occurs as a fine dendritic intergrowth with silica (Harvey *et al.*, 1996).

Opagques: Analyses for ilmenite and ulvöspinel are reported in Kring *et al.* (1996) and McSween *et al.* (1996).

Sulfide: The sulfide phase is pyrrhotite (McKay *et al.*, 1996, McSween and Eisenhour, 1996).

Glass: QUE94201 contains abundant pockets of shock-melted glass. This melt contains up to 7 % P, probably due to preferential melting of the abundant phosphates (Mikouchi *et al.*, 1996).

Salts: Fe-K-sulfates are sometimes observed rimming Fe-sulfides (Harvey *et al.*, 1996). The salts have been studied in detail by Wentworth and Gooding (1996). They found that “carbonates are conspicuously absent.”

Whole-rock Composition

QUE94201 is a basalt that is greatly depleted in LREE (figure XII-4). The composition has been determined by Mittlefehldt and Lindstrom (1996) and Warren *et al.* (1996). The sample has very high phosphorous content. This is also reflected in the analysis of the fusion crust (Kring *et al.*, 1996, Mikouchi *et al.*, 1996).

Radiogenic Isotopes

Borg *et al.* (1996) reported a Rb-Sr age ($\lambda_{\text{Rb}} = 1.39 \times 10^{-11} \text{ year}^{-1}$) of $327 \pm 11 \text{ Ma}$ with initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.701298 ± 12 (revised value, Borg, personal communication). This low I_{Sr} ratio indicates that the source region (Martian mantle) was depleted in Rb. The Sm-Nd age of 329 ± 42 with $\epsilon_{\text{Nd}} = 47.4 \pm 3.5$ is concordant with the Rb-Sr age (Borg, personal communication). Dreibus *et al.* (1996b) reported a K/Ar age of 1.33 Ga.

Cosmogenic Isotopes and Exposure Ages

From cosmic-ray produced ^3He , ^{21}Ne and ^{38}Ar , Eugster *et al.* (1996) computed an exposure age for QUE94201 of $2.4 \pm 0.6 \text{ Ma}$ and concluded that QUE94201 was “ejected from Mars simultaneously with the other basaltic shergottites - Shergotty and Zagami”. Nishiizumi and Caffee (1996) found the ^{10}Be concentrations gave a cosmic-ray exposure age of $2.6 \pm 0.5 \text{ Ma}$ for an assumed 4π irradiation geometry. Dreibus *et al.* (1996b) also reported exposure ages.

Nishiizumi and Caffee (1996) found that the terrestrial

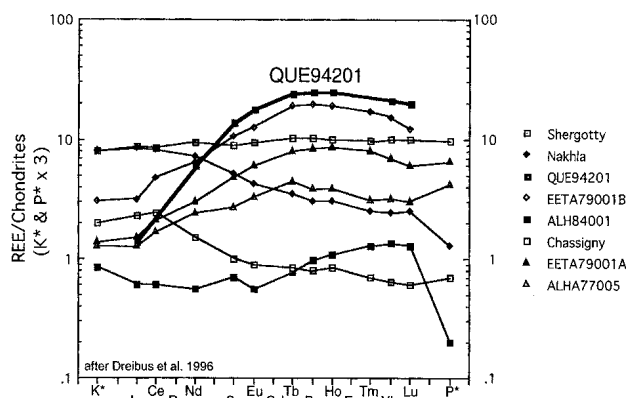


Figure XII-4. Normalized rare earth element diagram for QUE94201 compared with data for other Martian meteorites.

age ($0.29 \pm 0.05 \text{ Ma}$ obtained from ^{36}Cl) of QUE94201 is longer than for other Antarctic shergottites.

Other Isotopes

Oxygen isotopes were reported by Clayton and Mayeda (1996) (figure I-2). Leshin *et al.* (1996) have determined that the hydrogen in six apatite grains in QUE94201 has a high D/H ratio, probably from the Martian hydrosphere.

Grady *et al.* (1996) reported that the carbon released from 450 to 600°C was isotopically light ($\delta^{13}\text{C} \sim -24.2 \text{ ‰}$).

Swindle *et al.* (1996) determined the rare gas content and isotopic ratios of QUE94201 and found them typical of other shergottites.

Weathering

Wentworth and Gooding (1996) have studied the weathering products in QUE94201. They report an abundance of Fe-sulfate, but since this is also observed in cavities in the fusion crust, this is almost certainly of Antarctic origin (Harvey *et al.*, 1996).

Processing

This small sample (12.0 g) has some remnant fusion crust which is difficult to distinguish from interior glass. The sample was initially thought to be a terrestrial rock, but the presence of maskelynite in thin section revealed its Martian origin. Allocations were made from small interior and exterior chips. Two potted butts were used to produce 12 thin sections (table XII-2).

QUE 94201 is listed as a “restricted” sample by the MWG (Score and Lindstrom, 1993, page 5) because of its small size.

Table XII-2. QUE 94201 Thin Sections (12).

Potted Butt	Thin Section	Parent
,2	,3 Mason	,0
	,4 MCC	
	,5 McSween	
	,6 Harvey	
	,7 Kring	
	,8 Gooding	
	,9 Mittlefehldt	
	,34 Mikouchi	
	,35 Dreibus	
,20	,36 MCC	,0
	,37 Mittlefehldt	
	,38 Harvey	

Table XII-1. Chemical analyses of QUE 94201.

	Warren96		Dreibus96		Kring 96		Kring 96		Mikouchi96	
weight	305 mg		179.8 mg		250mg		fusion crust		fusion crust	
SiO ₂ %	47.06	(a)					43.5	(d)	44.3	(d)
TiO ₂	1.95	(a)	1.8	(b)	1.7	(b)	1.81	(d)	2	(d)
Al ₂ O ₃	9.64	(a)	12	(b)	11.1	(b)	7.46	(d)	7	(d)
FeO	18.65	(a)	18.3	(b)	18.3	(b)	24.2	(d)	21	(d)
MnO	0.48	(a)	0.436	(b)	0.44	(b)	0.63	(d)	0.6	(d)
CaO	11.3	(a)	11.3	(b)			10.9	(d)	11.2	(d)
MgO	6.3	(a)	6.2	(b)			6.04	(d)	6.4	(d)
Na ₂ O	1.39	(a)	1.75	(b)			1.16	(d)	1.1	(d)
K ₂ O	0.038	(a)	0.052	(b)			0.04	(d)		
P ₂ O ₃							2.77	(d)	3.4	(d)
sum	96.81						98.51		97.0	
Li ppm										
C										
F			40	(b)						
S										
Cl			91	(b)						
Sc	49	(b)	46.6	(b)						
V	124	(b)	103	(b)						
Cr	1030	(b)	890	(b)						
Co	24.4	(b)	22.8	(b)						
Ni	<40	(c)	<20	(b)						
Cu										
Zn	108	(c)								
Ga	26	(b)	27.1	(b)						
Ge										
As			0.77	(b)						
Se										
Br			0.35	(b)						
Rb				(b)						
Sr	59	(b)	80	(b)						
Y			31.2	(e)						
Zr	94	(b)	97.1	(e)						
Nb			0.68	(e)						
Mo										
Pd ppb										
Ag ppb										
Cd ppb										
In ppb										
Sb ppb										
Te ppb										
I ppm			4.6	(b)						
Cs ppm										
Ba	<41	(b)	<15	(b)						
La	0.44	(b)	0.35	(b)						
Ce	1.63	(b)	1.3	(b)						
Pr										
Nd	2.4	(b)	1.9	(b)						
Sm	2.55	(b)	2.02	(b)						
Eu	1.09	(b)	0.99	(b)						
Gd			4.3	(b)						
Tb	0.93	(b)	0.802	(b)						
Dy	6.1	(b)	5.53	(b)						
Ho			1.19	(b)						
Er										
Tm										
Yb	3.5	(b)	3.09	(b)						
Lu	0.54	(b)	0.455	(b)						
Hf	3.4	(b)	3.42	(b)						
Ta	<0.08	(b)	0.023	(b)						
W ppb										
Re ppb										
Os ppb										
Ir ppb	<2.4	(b)	<3	(b)						
Au ppb			<1.5	(b)						
Tl ppb										
Bi ppb										
Th ppm	<0.09	(b)	0.05	(e)						
U ppm			0.0125	(e)						

technique: (a) emp fused bead, (b) INAA, (c) RNAA, (d) emp, (e) spark source ms